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A numerical analysis of interface damage effect on mechanical properties of composite materials

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A B S T R A C T

Interfaces play an important role on macroscopic behaviors of composite materials. A number of studies have been devoted to analytical and numerical analyses of linear elastic interfaces. In this work, a new damage model is proposed to describe the progressive degradation of interfaces. The proposed model is implemented in the framework of extended finite element method. A series of numerical simulations performed. It is found that the interface damage induces a reduction of both macroscopic elastic stiffness and mechanical strength of composites. Further, related to the interface damage, we have also investigated the inclusion size effect on macroscopic behaviors of composites. It is found that the interface damage is enhanced by large size inclusions leading to a reduction of macroscopic damage threshold of materials.

1. Introduction

There are different kinds of interfaces in composite materials. In the present work, we consider a class of composites with a matrix/inclusion microstructure. The interfaces between the matrix and inclusions are represented by spring-layer imperfect curved surfaces which are characterized by the presence of displacement discontinuities (Duan et al., 2007; Shang et al., 1992). Different micromechanical models have been developed to establish the relationships between the imperfect interface properties and macroscopic mechanical behaviors of composites. Among others, we cite here the pioneer's works by Benveniste (1985) and Hashin (1991), who have initiated the analytical studies of the imperfect interface effects on the effective elastic properties of composite materials. Zhong and Meguid (1976) established an analytical elastic solution for an infinite matrix containing a spherical inhomogeneity coated by a spring-layer imperfectly bonded interface. More recently, Duan et al. (2007) proposed a unified homogenization scheme to predict the effective elastic moduli of multiphase composites with interface effects. Most studies so far developed are generally devoted to elastic properties of composites. However, in a class of quasi-brittle composite materials such as ceramics and concrete, the macroscopic mechanical behavior is mainly dominated by the growth of microcracks. Further, the initiation of microcracks is generally related to the debonding of interfaces (Ho and Fong, 2007; Ide et al., 1999; Rae et al., 2002a,b; Sciammarella and Sciammarella, 1998; Tan et al., 2007; Zhou et al., 2004). Some authors (Shang et al., 1992; Aboudi, 1987; Ju and Lee, 2000, 2001; Lee, 2007; Tan et al., 2005a,b) have investigated nonlinear behaviors of composites by considering a nonlinear elastic relation for interfaces. There are also some micromechanical models (Ju and Lee, 2000, 2001; Lee, 2007), based on a probabilistic approach, in order to modeling interface debonding by considering an elastic-brittle behavior for interface. Most of these works do not consider the irreversible damage of interfaces and are often limited to two-dimensional cases. In the present work, we propose to formulate a new damage model for interfaces by the definition of a specific damage evolution law as a function of interface displacement discontinuities. This damage model is able to describe the progressive degradation of mechanical properties of interfaces during loading process. On the other hand, the proposed model will be implemented in a three-dimensional computer code using the extended finite element method (XFEM) to describe displacement discontinuities at interfaces.

Related to the interface deformation and damage, another important issue for composite materials is the influence of inclusion size on the macroscopic mechanical behavior. For instance, Benveniste (1985) studied the effective mechanical behavior of composites with imperfect contacts between particles and matrix and found a strong dependence of the effective properties of

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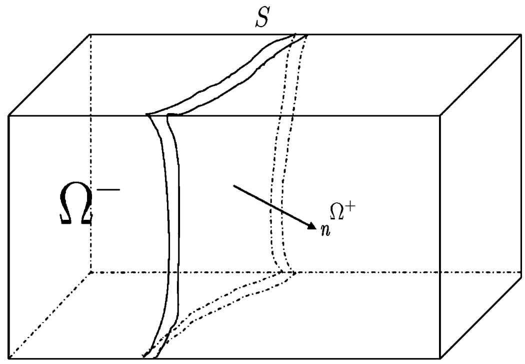

Fig. 1. Basic spring-layer interface model.

composites on the inclusion size. By making use of homogenization technique, Duan et al. (2007) derived two scaling laws to capture the size-dependence for multiphase composites presenting imperfect interfaces. Based on the energy criterion initially defined by Griffith (1920), Bhattacharya et al. (1998) proposed an energy-based failure model for compressive splitting of polycrystals, showing that the failure strength decreases as the grain size increases. In addition, Cho et al. (2006) pointed out that the interface debonding process for small particles required higher stresses than for large particles. Quesada et al. (2009) studied the compressive strength of the composite with a rigid inclusion embedded in a soft matrix and proposed a mixed criterion as a function of both energy and stress to establish the relationship between the inclusion size and mechanical strength. On the other hand, the extended finite element method (XFEM) has been applied to modeling imperfect interface effects for both coherent interfaces (Yvonnet et al., 2008; Zhu, 2012) and spring-layer interfaces (Zhu, 2012; Zhu et al., 2011) in the elastic domain. In the present work, the size effect will be investigated by taking into account the damage process of interface and using 3D XFEM framework.

The present paper is organized as follows. The formulation of the interface damage model is first presented. We will define the XFEM framework for 3D modeling of imperfect interfaces using the proposed damage model. Numerical results will be finally presented and discussed to investigate consequences of interfaces damage and inclusions size effects.

2. Formulation of the interface elastic-damage model

In the spring-layer interface, the displacement field is discontinuous across the interface while the stress vector is continuous. Consider two adjacent domains Ω^+ and Ω^-, separated by a spring-layer interface S, as shown in Fig. 1. The interface is assumed to be smooth with the unit normal vector $\boldsymbol{n}$ directed from Ω^- to Ω^+. The displacement jump vector is denoted by $[\boldsymbol{u}]$ and the traction vector at the interface is $\boldsymbol{t}$. The mechanical behavior of the spring-layer interface can be described by the following relation (Hashin, 1991; Zhu et al., 2011):

$$\boldsymbol{t} = \boldsymbol{C}^s \cdot [\boldsymbol{u}] \tag{1}$$

where $\boldsymbol{C}^s$ is the second order elastic stiffness tensor which is positive definite. When the behavior of interface is isotropic and linear, the local interface stiffness is written by:

$$\boldsymbol{C}^s = \lambda^s \boldsymbol{n} \otimes \boldsymbol{n} + \mu^s (\delta - \boldsymbol{n} \otimes \boldsymbol{n}) \tag{2}$$

λ^s and μ^s denote respectively the normal and tangential moduli of the interface.

We assume that during mechanical loading, the interface is progressively debonded. This is interpreted by the degradation of elastic properties of the interface. Further, under tensile stress, the interface is degraded by the normal opening. Under compressive stress, two surfaces of the interface are in contact and the interface degradation is controlled by the tangential sliding. Therefore, we introduce here two independent damage variables ω_n and ω_t, in order to describe the normal and tangential degradation of interfaces. The two damage variables are defined by:

$$\omega_n = 1 - \exp(-b_1 \varepsilon_n) \tag{3}$$

$$\omega_t = 1 - \exp(-b_2 \varepsilon_t) \tag{4}$$

with:

$$\varepsilon_n = \frac{[\boldsymbol{u}_n]}{h}, \quad \varepsilon_t = \frac{\left\|[\boldsymbol{u}]\right\|}{l} \tag{5}$$

Two parameters b_1 and b_2 are introduced to define the kinetics of the normal and tangential damage of interfaces. Note that in real composite materials, there is a transition zone between different constituent phases. The transition zone is here idealized by the spring-layer interface. The parameters h and l denote the characteristic thickness and length of the transition zone respectively. Considering that the normal modulus is affected by the normal damage while the shear modulus is affected by the both normal and tangential damage. The stiffness tensor $\boldsymbol{C}^s$ of damaged interface can be expressed in the following form:

$$\boldsymbol{C}^s(\omega_n, \omega_t) = \lambda^s(\omega_n) \boldsymbol{n} \otimes \boldsymbol{n} + \mu^s(\omega_n, \omega_t) \left(\delta - \boldsymbol{n} \otimes \boldsymbol{n}\right) \tag{6}$$

In this work, we adopt the following linear forms to define the damage effect on the elastic moduli of interface:

$$\lambda^s(\omega_n) = \lambda_0^s (1 - \omega_n) \tag{7}$$

$$\mu^s(\omega_n, \omega_t) = \mu_0^s (1 - \omega_n - \omega_t) \tag{8}$$

$\lambda^s(\omega_n)$ and $\mu^s(\omega_n, \omega_t)$ denote the normal and tangential moduli of the damaged interface while λ_0^s and μ_0^s are their initial values at the undamaged state.

3. XFEM framework for 3D interface modeling

Based on the previous works (Zhu et al., 2011; Moës et al., 1999), we briefly present the XFEM framework for the numerical modeling of 3D imperfect interfaces by taking into account the interface damage. In Fig. 2, we show the boundary value problem (BVP) to be solved in the composite constituted by a matrix and embedded inclusions. Consider a representative volume element (RVE) of a composite with $n+1$ constituent phases and occupying a volume Ω with an external boundary S. Let Ω_r and f_r denote the domain occupied by and the volume fraction of the r^{th} constituent phase. For the sake of simplicity, $r = 0$ denotes the matrix phase. S_r defines the interface between the matrix and the r^{th} phase of inclusion. The local boundary value problem is formulated by the following governing equations:

$$\sigma^r = \mathbb{C}^r : \varepsilon^r, \quad \text{in} \quad \Omega_r \tag{9}$$

$$\text{div}\sigma^r = 0, \quad \text{in} \quad \Omega_r \tag{10}$$

$$\varepsilon^r = \frac{1}{2}(\nabla \boldsymbol{u}^r + {}^T\nabla \boldsymbol{u}^r), \quad \text{in} \quad \Omega_r \tag{11}$$

$$\boldsymbol{t}^r = \boldsymbol{C}^{s,r} \cdot [\boldsymbol{u}]^r, \quad \text{on} \quad S_r \tag{12}$$

$$\boldsymbol{u} = \boldsymbol{u}_0, \quad \text{on} \quad S_{u_0} \tag{13}$$

$$\sigma^0 \cdot \boldsymbol{m} = \boldsymbol{t}_0, \quad \text{on} \quad S_{t_0} \tag{14}$$

In the present work, the body force is neglected. By applying the virtual work theorem to the RVE, we obtain the weak formulation